Performance Considerations of Code Division Multiple-Access Systems

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Abstract—**The performance of code division multiple-access (CDMA) systems is determined using direct-sequence spectral spreading. Asynchronous users are assumed so that there is no network control. Under relatively ideal conditions, the degradation in system performance as a function of the number of users is shown to have a threshold effect. This basic limitation in the number of users of the system is further limited if the powers are unequal. For two users, system performance as a function of their power ratios also has a threshold effect. System performance as a function of the amount of spectral spreading is determined. The performance of both coded and uncoded systems is predicted.**

I. INTRODUCTION

MULTIPLE ACCESS can be achieved by spread-spectrum code division using direct-sequence pseudonoise, frequency hopping, time hopping, and hybrids, or combinations of these techniques. A primary necessity of such systems is the requirement for sets of spreading signals which have the two properties that 1) each signal can easily be distinguished from a time-shifted version of itself, and 2) each signal can be easily distinguished from every other signal in the set. Pseudonoise multiple access consists of spread-spectrum code division attained by the use of binary maximal-length linear feedback shift register sequences which are often called *m*-sequences [1].

We consider sets of asynchronous users only. As a result, there is no network control. We shall show that asynchronous code division multiple-access (CDMA) is limited primarily by the number of users in the network.

The communication performance of phase-coded CDMA when the bit period is equal to the code period or multiples of it has been evaluated by Pursley and coworkers [2]-[6] for both *m*-sequences and Gold codes. We designate such cases as short codes, and we will see that the results obtained herein for long codes are similar to those obtained for short codes.

This paper discusses the number of users that can be accommodated in a direct-sequence spread-spectrum multiple-access system. As opposed to the operations of acquisition and tracking, we consider only communication performance and use the probability of bit error as the performance measure.

Manuscript received July 5, 1980; revised November 5, 1980. This work was supported in part by the Army Research Office under Grant DAAG29-79-C-0054 and in part by the Axiomatrix Corporation.

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It is a formidable task to develop exact generalized results that are meaningful for the probability of error. This discussion is therefore limited to the idealized assumptions that the matched filter in the receiver for the desired signal is perfectly synchronized in 1) frequency, 2) phase, 3) chip epoch, and 4) bit epoch.

The first task is to determine a satisfactory model for the effect of the other users in the receiver matched to the desired signal. In this regard, we consider the following.

Many chips are assumed to occur within each bit duration. The code is assumed to be sufficiently long that one period of the code, at most, occurs during each bit duration. The purpose of this assumption is to conclude that the effect of all other users on the receiver output matched to the desired signal is approximately a Gaussian random variable. We desired this conclusion independent of which class of code division sequences is employed. Towards this end, we make the following observations.

When the code division sequences are samples of purely random sequences, the above assumptions allow us to conclude that the effect of the other users can be effectively modeled as Gaussian random processes and that their power spectral densities are essentially flat within the data bandwidth.

When specific deterministic code sequences are employed, however, the situation is somewhat more complex. During each bit period, the effect of each of the other users consists of a partial-period cross correlation between the code sequence of the other users and that of the desired signal. In fact, when binary phase-shift keyed (BPSK) data modulation is taken into account, the effect of each of the other users may consist of the sum of two such partial-period cross correlations. Whether this effect consists of one or two cross correlations depends on whether or not a data transition by the other user occurs during the bit period of the desired signal. In either condition, we want to draw the same conclusion as in the purely random case.

For this, we need to examine these partial-period cross correlation values for specific code sequences. A complete statistical description of the set of all partial-period cross correlation values for a class of code division sequences would be ideal. This is overly ambitious, but estimates of the probability function have been found. In order to obtain estimates of the probability function, upper and lower bounds can be developed from knowledge of the first L moments (i.e., the moment problem). As the number of moments taken into account is increased, the bounds become tighter. The moment problem approach has been applied by Bekir *et al.* [7], [8] to

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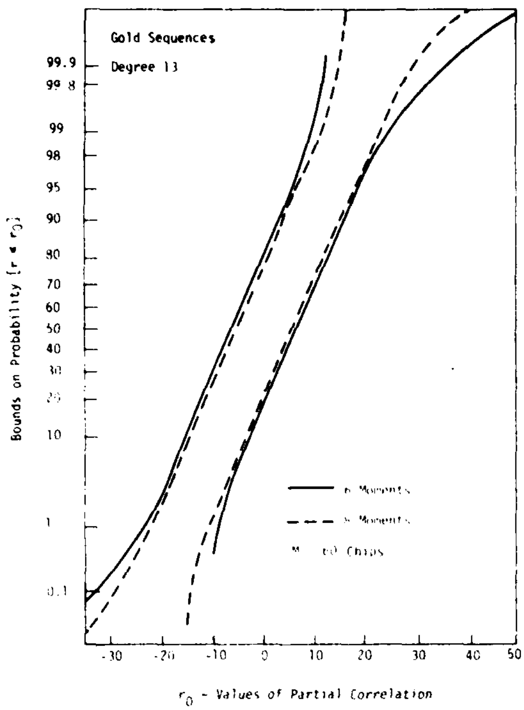

Fig. 1. Bounds on probability $[r < r_0]$ versus r_0 for set of Gold sequences of degree 13 and observation window of 60 chips.

obtain upper and lower bounds on the probability functions for all cross and nonsynchronous autocorrelation values for sets of pseudonoise (PN) sequences and Gold sequences.

Fig. 1 shows results for the class of Gold sequences of degree 13 where the partial-period correlation is with $M = 60$ chips. The results are plotted on Gaussian probability paper wherein the probability function for a Gaussian random variable is a straigth line. The upper and lower bounds which result from the first six and first eight moments are shown. It is seen that the use of the first eight moments provides bounds which are tighter than those for the first six moments and closer to the straight-line estimate we desire. The conclusion to be drawn from these results is that, for the set of Gold sequences of degree 13, the effect of the sum of the other users in the receiver matched to the desired signal can be effectively modeled as a Gaussian random variable. Bekir *et al.* concluded that in many, but not all, cases, the partial-period correlation of PN sequences and classes of Gold sequences can be effectively modeled as a Gaussian random variable.

The computations of Bekir, however, did not include the effects of data. It is conjectured that, for the case of many code chips per bit duration, the effect of a data reversal will not negate the Gaussian conclusions. In fact, it is expected that the Gaussian assumption becomes even more justified.

There are a variety of other Gaussian approximations which have been developed for the effects of other users in a direct-sequence CDMA environment. The specific approximation developed by Pursley [3] has been shown to be accurate for code periods and number of users of practical interest. The quality of these approximations was subsequently shown to be excellent by Pursley *et al.* [5], [6] and Yao [9] for code periods greater than seven.

Given that the Gaussian assumption is accurate for both random sequence sets of codes and specific sets of deterministic codes (e.g., sets of Gold sequences), the difference which can still occur is in the evaluation of the variance of the resulting random variable. When the partial-period cross correlations of a set of specific codes are enumerated, the resulting variance of the approximately Gaussian random variable may differ from that obtained from sets of random sequences.

In the next section, we develop the performance of asynchronous direct-sequence CDMS systems based on the assumption that the code sequences are samples of purely random sequences. In so doing, we will point out that a "scale factor" enters which accounts for the difference in performance between CDMA systems employing purely random code sequences and those employing sets of specific deterministic sequences. We do not attempt to evaluate this important parameter precisely for any set of specific sequences. This has been carefully addressed by Pursely *et al.* [3]-[6].

Our goal here is to obtain a preliminary prompt assessment of what can be expected from a direct-sequence CDMA system, particularly from long codes with many chips per bit duration. The development of CDMA system performance in the next section is based on these assumptions and a set of purely random sequences for direct-sequence code division.

II. DEVELOPMENT OF SYSTEM PERFORMANCE

The performance of a class of code division multiple-access systems is determined under ideal conditions. The purpose is to obtain an initial look at the performance of code division multiple-access spread-spectrum communication systems. The approach emphasizes average performance in relatively ideal conditions, as opposed to worst-case performance [3].

The total number of users of the channel is designated as n. These users have powers $P_0, P_1, \cdots, P_{n-1}$, respectively, and these are the effective powers through the entire communication link. Assuming that the signal with power P_0 is that of the desired user, we define

$$\alpha_i = P_i/P_0, \qquad i = 1, \cdots, n-1 \tag{1}$$

as the power ratio of the ith user to the desired user. These are then the effective power ratios at the zeroth receiver.

We make the following simplifying assumptions.

1) All users communicate via a single-channel BPSK digital link at a common carrier frequency f_c and data rate $R_b = 1/T_b$, where T_b is the symbol duration.

2) All users have the same chip rate for their PN code division sequence, i.e., $R_c = T_c^{-1}$, where T_c is the chip time.

3) Performance estimates are based on ideal matched-filter receivers. The probability of bit error for BPSK, assuming the additive white Gaussian noise channel, is then given by

$$P_b = Q((2E_b/N_0)^{1/2}) \tag{2}$$

where E_b/N_0 is the ratio of the signal energy per data bit to the one-sided noise power spectral density (PSD) and $Q(x)$ is the Gaussian integral function defined by

$$Q(x) \triangleq \int_x^{\infty} (2\pi)^{-1/2} \exp(-u^2/2)\, du. \tag{3}$$

For ideal BPSK, the values of P_b and E_b/N_0 which are typically of interest are as follows: $P_b = 10^{-4}$, 10^{-5}, and 10^{-6}, and $E_b/N_0 = 8.4$ dB, 9.6 dB, and 10.5 dB, respectively.

In the absence of other users, the ratio of the signal energy to noise PSD for the desired signal is given by

$$E_b/N_0 \triangleq (E_b/N_0)_1 = P_0/(R_b N_0) \tag{4}$$

where N_0 is the overall one-sided PSD of the noise and the subscript 1 implies that the channel is occupied by only one user. This value of E_b/N_0, necessary to produce a given probability of bit error (e.g., 10^{-5}) in the single-user BPSK system which we define as $(E_b/N_0)_1$, is one of our important quantities.

4) In the presence of other users, the effect on the desired user is assumed to consist of additional broad-band noise, as discussed in the previous section. This additional broad-band noise is assumed to be additive. Equivalently, we assume that the channel is linear.

If the user's signals are mutually noncoherent, their PSD's add. If the ratios for $R_c/R_b = T_b/T_c$ are large, the only values of PSD's of significance are those in the vicinity of $f = f_c$. The equivalent one-sided PSD near $f = f_c$ due to the ith other user at the front end of the receiver matched to the desired signal is given by

$$N_i = P_i/R_c = P_i T_c = \alpha_i P_0 T_c. \tag{5}$$

Equivalently, the other users appear as broad-band noise at the front end of the receiver matched to the desired signal, and the despreading operation in the receiver does not affect the statistics of these equivalent noises. There is an increase, therefore, in the effective PSD from all other users at the front end of the receiver for the desired signal. The actual signal energy to noise PSD for the receiver matched to the desired signal is therefore given by

$$\left(\frac{E_b}{N_0}\right)_n = \frac{E_b}{N_0 + \sum_{i=1}^{n-1} N_i} \tag{6}$$

when n users are present. We shall designate this as signal-to-noise ratio (SNR), i.e., $(E_b/N_0)_n$ = SNR is what is actually seen at the receiver when n users are present. Clearly, there has been a reduction in $(E_b/N_0)_n$ due to the presence of the other users from that of the signal user case, i.e., $(E_b/N_0)_n < (E_b/N_0)_1$, $n > 1$.

In order to maintain the same probability of bit error when n users are present as obtained for the single-user case, the value of $(E_b/N_0)_n$ must be increased to $(E_b/N_0)_1$. We designate by $(E_b/N_0)_R$ the *required* single user E_b/N_0 necessary to make the n-user SNR, namely, $(E_b/N_0)_n$ equal to $(E_b/N_0)_1$. Substituting (5) into (6) and using $(E_b/N_0)_R$ for required E_b/N_0, the actual SNR in (6) can be expressed as

$$\left(\frac{E_b}{N_0}\right)_n = \frac{(E_b/N_0)_R}{1 + \eta^{-1}(E_b/N_0)_R\left(\sum_{i=1}^{n-1}\alpha_i\right)} = \left\{(E_b/N_0)_R^{-1} + \eta^{-1}\left(\sum_{i=1}^{n-1}\alpha_i\right)\right\}^{-1} \tag{7}$$

where $\eta \triangleq T_b/T_c = R_c/R_b$ is defined as the ratio of the code rate to the data rate.

The actual SNR, namely, $(E_b/N_0)_n$, is what is usually constrained to be at or above some design specification when n users are present. The E_b/N_0 (based on one user) required to meet the system specification for the actual SNR ($(E_b/N_0)_n$) when n users are present is what we have designated as $(E_b/N_0)_R$. Finally, the specification value for $(E_b/N_0)_n$ is that it be increased to $(E_b/N_0)_1$. The specified value of probability of bit error is therefore attained. If we set $(E_b/N_0)_n \mp (E_b/N_0)_1$ in (7), then the SNR will meet the specified value. Solving for the *required* E_b/N_0 in (7), we obtain

$$\left(\frac{E_b}{N_0}\right)_R = \frac{(E_b/N_0)_1}{1 - \eta^{-1}(E_b/N_0)_1\left(\sum_{i=1}^{n-1}\alpha_i\right)}. \tag{8}$$

It is also convenient to examine the increase in required E_b/N_0, i.e., $(E_b/N_0)_R$ necessary to maintain $(E_b/N_0)_n = (E_b/N_0)_1$. For this, we normalize (8) and compute the *degradation factor* (DF), defined as the ratio of the required E_b/N_0 for the receiver matched to the desired signal, namely, $(E_b/N_0)_R$, when n users are present, to that needed to meet the specified value of probability of bit error when there is one user. Therefore,

$$\text{DF} = \frac{(E_b/N_0)_R}{(E_b/N_0)_1} = \frac{1}{1 - \eta^{-1}(E_b/N_0)_1\left(\sum_{i=1}^{n-1}\alpha_i\right)}. \tag{9}$$

This is a general result under the ideal conditions specified above in that it applies for any number of users, arbitrary power ratios, all values of SNR, and all values of $\eta = R_c/R_b$ which are large enough that the Gaussian noise assumption applies for modeling the effects of the other users. Clearly, when the SNR is equal to $(E_b/N_0)_R$ and there is only one user, the probability of bit error is reduced from the specified value by as much as several orders of magnitude.

Further observation of (7) and (9) provides the following: the key point in (7) is that, as n increases, $(E_b/N_0)_R^{-1}$ must decrease in order to keep the right-hand side of (7) constant. Ultimately, however, no amount of increase of $(E_b/N_0)_R$ can offset the increase in the other terms. As a result, the number of users can be increased so that the DF in (9) becomes infinite.

III. EVALUATION OF SYSTEM PERFORMANCE

We now apply this generalized result to estimate system performance for some illustrative examples.

Example 1: n Equal-Power Users, Uncoded

When there are n equal-powers users, then $\alpha_i = 1$ for all i, and (9) becomes

$$\text{DF} = \frac{1}{1 - (n-1)\eta^{-1}(E_b/N_0)_1}. \tag{10}$$

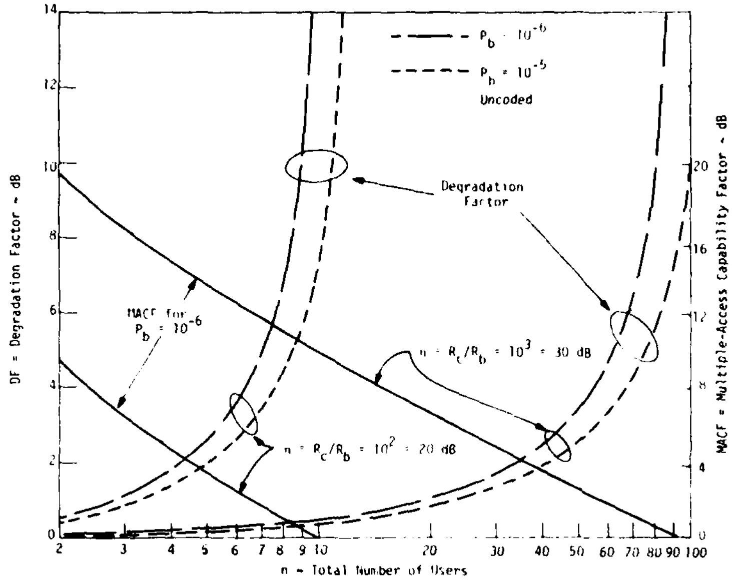

Fig. 2. System performance for n equal-power users.

In (10), we note that $(E_b/N_0)_R \rightarrow (E_b/N_0)_1$ as $n \rightarrow 1$, as would be expected with only the desired user present.

Rewriting (7) for n equal-power users, we have

$$\left(\frac{E_b}{N_0}\right)_n = \frac{(E_b/N_0)_R}{1 + (n-1)\eta^{-1}(E_b/N_0)_R}. \tag{11}$$

In (11) we note that, for large values of $(E_b/N_0)_R$,

$$\lim_{(E_b/N_0)_R \rightarrow \infty} \left(\frac{E_b}{N_0}\right)_n = \frac{\eta}{(n-1)}, \qquad n \geqslant 2. \tag{12}$$

This is the largest value that the SNR $= (E_b/N_0)_n$ can attain. With this motivation, we define the *multiple-access capability factor* (MACF) as the limiting factor in (12), namely, $\eta/(n-1)$ normalized by the SNR, $(E_b/N_0)_n$. Hence

$$\text{MACF} \triangleq \frac{\eta}{(n-1)}\left(\frac{E_b}{N_0}\right)_n^{-1} \tag{13}$$

which, via (11), can also be expressed as

$$\text{MACF} = \frac{\eta}{(n-1)}\left(\frac{E_b}{N_0}\right)_n^{-1} = \frac{\eta}{(n-1)}\left(\frac{E_b}{N_0}\right)_R^{-1}. \tag{14}$$

We see in (14) that, as long as the desired SNR, namely, $(E_b/N_0)_n$, is such that the left-hand side is greater than or equal to one, we can achieve that SNR by appropriately adjusting $(E_b/N_0)_R$ in the right-hand side. If the left-hand side is less than one, however, no value of $(E_b/N_0)_R$ will give the desired value of $(E_b/N_0)_n$.

The expression for $(E_b/N_0)_n$ in (11) for n equal-power users is similar to that obtained by Pursley [2] with a different approach for asynchronous direct-sequence CDMA systems, where the code length is equal to $\eta = R_c/R_b$. The difference is a *scale factor* in the second term of the denominator which may be unimportant for random sequences [3] but *is* important for specific direct-sequence codes. Variations in this scale factor will also alter the range of values of $(E_b/N_0)_n$ in (14) where the desired performance values can be attained. This scale factor is dependent on the statistics of the partial-period cross correlation values of the set of code sequences employed, as mentioned in the introduction.

The system performance for n equal-power users described in Fig. 2 shows the degradation factor versus the number of users n as given in (10). For $P_b = 10^{-6}$, $(E_b/N_0)_n$ must be 10.5 dB. The additional SNR required to maintain this error rate is shown versus the number of additional users. The curve quantitatively provides the trade-off between SNR, number of users, and amount of spectral spreading (or bandwidth utilized). The difference in performance between a probability of error of 10^{-5} and 10^{-6} is very small. This is because the corresponding change in $(E_b/N_0)_n$ is small (0.9 dB).

For $P_b = 10^{-6}$ the *multiple-access capability factor* in (14) is also shown. It is clearly noted in Fig. 2 that, when the MACF reduces to 0 dB, the specification performance cannot be attained. For values of n equal to 10^2 and 10^3, this failure occurs when the total number of users is in the vicinity of ten percent of η. For both $P_b = 10^{-5}$ and 10^{-6}, when the total number of users is less than or equal to five percent of η, the DF can be maintained less than 4 dB. This corresponds to a MACF of approximately 2 dB.

Example 2: n = 2 Users of Different Powers, Uncoded

Set $\alpha = P_1/P_0$ in (9), from which we find that the degradation factor becomes

$$\text{DF} = [1 - \alpha\eta(E_b/N_0)_2]^{-1}. \tag{15}$$

Comparing this result with (10) shows that the performance is

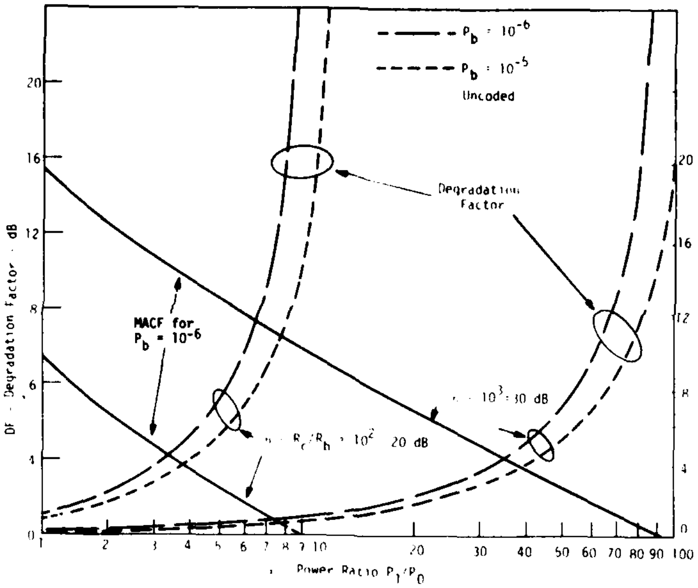

Fig. 3. System performance for two users of unequal power.

equivalent to n users for the equal-power example when we substitute $\alpha = n - 1$. This is to be expected, particularly since we have modeled additional users as adding more broad-band noise.

For simplicity of interpretation, the results of Fig. 2 are presented in Fig. 3 as a function of $\alpha = n - 1$. This example also models the "near/far" problem in which one interferer may have the same average transmitted power as the desired signal, but is geographically much closer.

Example 3

As a final uncoded case, a specific, more cumbersome example is presented. Assume that $n = 49$ users, and $\alpha_i = 0$ dB, $i = 1, \cdots, 8$; $\alpha_i = 2$ dB, $i = 9, \cdots, 16$; $\alpha_i = 4$ dB, $i = 17, \cdots, 24$; $\alpha_i = 6$ dB, $i = 25, \cdots, 32$; $\alpha_i = 8$ dB, $i = 33, \cdots, 40$; $\alpha_i = 10$ dB, $i = 41, \cdots, 48$. For this set of values, the degradation in performance due to the presence of the additional users, as specified in (9), is plotted in Fig. 4. The additional SNR required to maintain the specified probability of error per bit is plotted versus the ratio of code sequence chip rate to data rate. Probabilities of error per bit of 10^{-4}, 10^{-5}, and 10^{-6} are presented, and, again, it can be observed that dependence on the choice of probability of error is not significant.

The amount of spectral spreading as given by R_c/R_b is a dominant parameter. There is a definite threshold effect occurring in all of these performance curves. Equivalently stated, as the data rate is increased or the chip rate is decreased, the degradation in performance is gradual only in specific regions of R_c/R_b.

In the remaining examples, the first three examples are reexamined in the presence of coding. Specifically, a constraint length $K = 7$, rate $R = 1/2$ convolutional code is considered with Viterbi decoding and eight-level soft decisions. A summary of the performance of this code [10] in the presence of additive white Gaussian noise appears in Table I for probabilities of error or 10^{-6} to 10^{-3}. Its effect on the

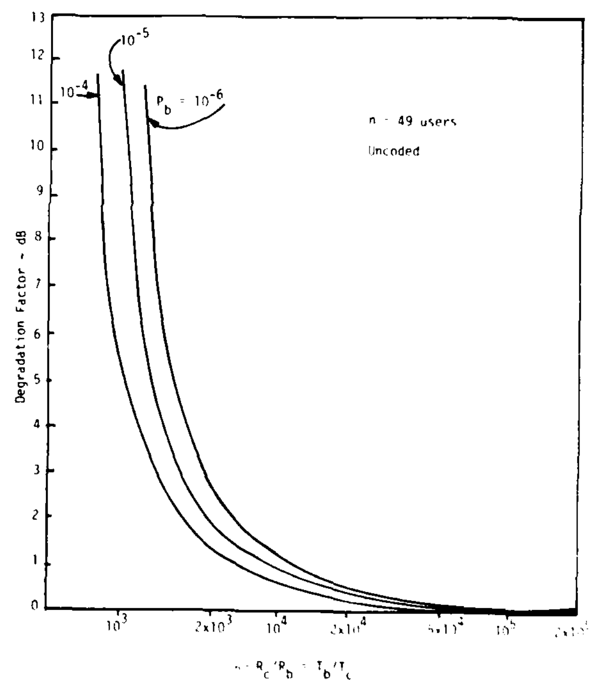

Fig. 4. System performance for user configurations specified in Example 3.

TABLE I

P_b	Uncoded E_b/N_0	Coded* E_b/N_0	Coded** E_s/N_0
10^{-6}	10.5 dB	5.0 dB	2.0 dB
10^{-5}	9.6	4.5	1.5
10^{-4}	8.4	3.8	0.8
10^{-3}	6.8	3.0	0.0

* SNR per message bit.
** SNR per channel symbol.

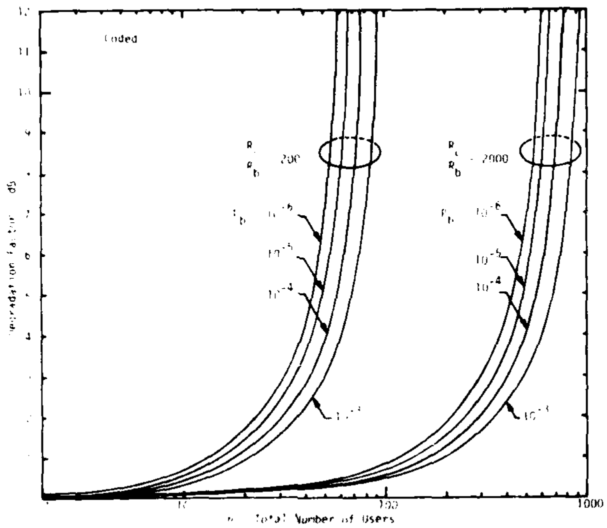

Fig. 5. Degradation factor versus total number of users with $K = 7, R = 1/2$ convolutional coding and Viterbi decoding with soft decisions.

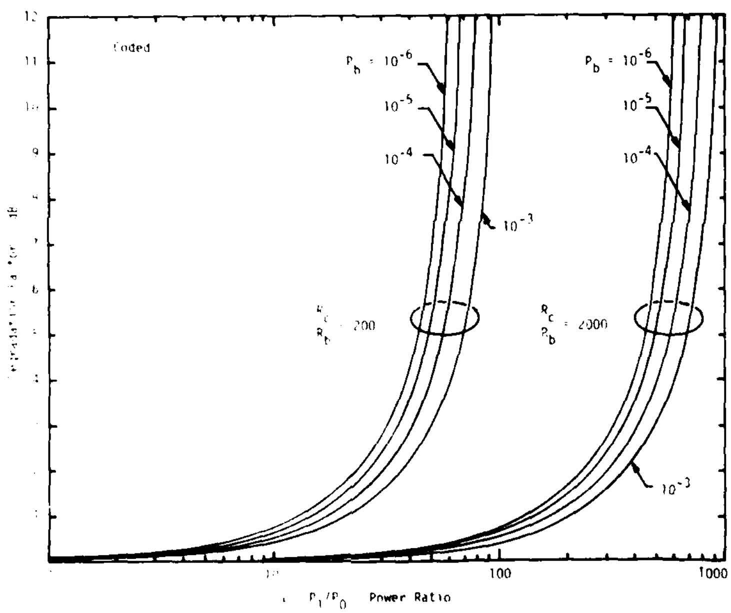

Fig. 6. Degradation factor versus power ratio for two users with $K = 7, R = 12$ convolutional coding and Viterbi decoding with soft decisions.

performance of a CDMA system shows up in E_s/N_0, the last column of Table I. As expected, these values are substantially less than E_b/N_0 for the uncoded case.

Example 4: n Equal-Power Users, Coded

The degradation factor for n equal-power users, using the values of $(E_s/N_0)_n$ which appear in Table I for the convolutionally coded system described above, appears in Fig. 5. The threshold effect in system performance is similar to the uncoded case. For a given error rate, the number of additional users that can be handled by coded systems at a given degradation factor can be determined from Figs. 2 and 5.

Coding is of no value during acquisition. In fact, at these lower values of operating $(E_s/N_0)_n$ in coded systems, the acquisition time can be expected to be substantially larger than in uncoded systems.

Example 5: $n = 2$ Users of Different Powers, Coded

The performance of two CDMA system users with different powers who employ the coding scheme described above is shown in Fig. 6. As in all of the previous cases, the degradation in performance is gradual until the vicinity of the threshold. In both this and the previous example, the effect on degradation factor of the required probability of error is not nearly as dramatic as the processing gain.

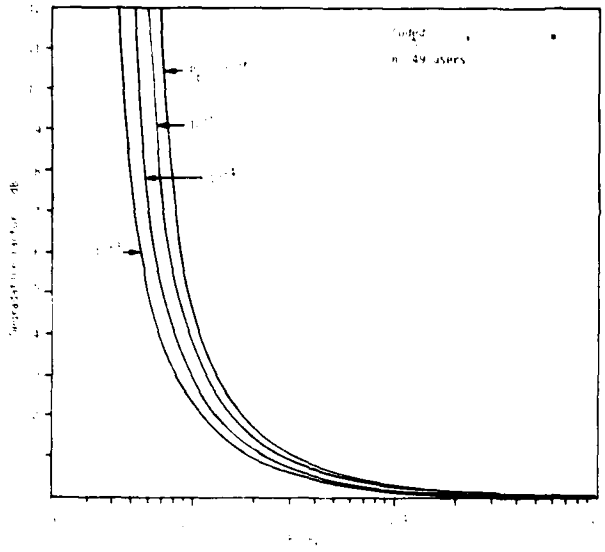

Fig. 7. Degradation factor versus R_c/R_b for variance error rates with $K = 7$, $R = 12$ convolutional coding and Viterbi decoding with soft decisions.

Example 6

The final case is a reexamination of Example 3 in the presence of coding. The amount of spectral spreading is seen to be a dominant parameter whether coding is present or not. The performance in this example is similar to the uncoded case, with the exception that substantially less spreading (i.e., bandwidth) is required. This can be seen by comparing Figs. 4 and 7.

IV. CONCLUSION

Under relatively ideal conditions, degradation in system performance as a function of the number of users is shown to be gradual. However, there is a pronounced threshold region above which performance degrades very rapidly. The degradation in system performance experiences the same effect when two users of different powers are considered. Performance as a function of the amount of spectral spreading also experiences the same degradation. Error-correcting coding extends the number of multiple-access users and reduces the amount of spectral spreading needed to attain a given performance level.

This development provides an approximate prediction of the performance of an asynchronous phase-coded CDMA system. The basic results are sufficiently general, however, that the performance for any number of users at arbitrary power ratios with the desired user can be predicted. The results are expected to be accurate, particularly for long codes and for situations where the Gaussian interference assumption is a good one.

ACKNOWLEDGMENT

The authors wish to express their appreciation for the helpful suggestions of the guest editor, Prof. Mike Pursley, as well as the anonymous reviewers.

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(18) HKO1

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER (14) 15943.18-EL	2. GOVT ACCESSION NO. N/A AD-A103 564	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) (6) Performance Considerations of Code Division Multiple-Access Systems		5. TYPE OF REPORT & PERIOD COVERED Reprint
		6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) (10) Charles L. Weber, Gaylord K. Huth, Bartus H. Batson	(15)	8. CONTRACT OR GRANT NUMBER(s) DAAG29-79-C-0054
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Southern California, Los Angeles, CA 90007	(11) 5 Jul 80	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N/A
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office, P. O. Box 12211, Research Triangle Park, NC 27709	(12) 7	12. REPORT DATE Feb 81
		13. NUMBER OF PAGES 8
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Submitted for announcement only.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

81 9 01 059

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified 391560

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